Correlation Between Vortex Structures and Aerodynamic Force in Insect’s Flight

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Abstract: The purpose of this research is to clarify generation mechanism of aerodynamic force of flapping airfoil imitating insect’s flight. Hovering flights are important to develop micro air vehicles (MAV) for rescue inquiry devices of disaster area. In order to understand hovering flights of insects, aerodynamic lifting force and flow field around a flapping machine was measured by using time-series analysis of PIV and numerical simulation. PIV measurements were carried out with the flapping machine which was 10 times expanding model of real insects. Experimental results showed a flapping airfoil holds a strong vorticity near the bottom dead center. The leading-edge vortex and the wake-capture process were observed by the PIV measurement, which are important to understand insect’s flight. Moreover, these processes generate large amount of aerodynamic force compare to the sinusoidal flapping motion. It reveals that feathering motion is important to realize the hovering flight.

1. Introduction

In order to develop micro air vehicles (MAV) for rescue inquiry device of disaster area, it is required to realize hovering flights imitating insect's flight. Over the past few decades, a considerable number of studies have been made on using examples from insect's or bird's flight (Thomas, J. Mueller (2001)). Although a large number of studies have been made on developing many kinds of MAV in the world, little is realized hovering flights by flapping motion. In small insects, the shape of the leading-edge of its wings is acute, which generates large separated flow. This strong vorticities generate negative-pressure field above the insects’ wings. This negative-pressure is used to lift the insects. This large separated vortex is known as "Leading-Edge Vortex".

In the sinusoidal flapping motion, the downstroke and upstroke makes lifting force and negative lifting force, respectively. Therefore, it is required to reduce the negative-lift caused by the upstroke motion for hovering flights. Insects reduce the negative-lift with twisting their wings in the upstroke motion. Moreover, they generate lifting force by using vorticity field.

Since the flight speed is slower than that of the flapping motion, the vorticities of the downstroke are kept around the insects. Insects capture this wake flow for hovering flights. This is well known as "Wake-Capture" of the insects' flights.

The aim of this investigation is to develop the MAV imitating insect's motions to realize the hovering flights. For this purpose, the vorticity fields were visualized by using Particle Image Velocimetry (PIV) measurements and numerical simulation. Moreover, aerodynamic forces of the flapping airfoil were estimated with the discrete vortex method.

2. Experimental and Numerical Methods

2.1. PIV System

In order to clarify “Leading-Edge Vortex” and “Wake-Capture”, two-dimensional vorticity field measurements are required. PIV is useful to estimate the vorticity field around the flapping airfoil. The experiments were carried out by using the “sharpVISION PIV system” of IDT. The cross-correlation method and the frame straddling technique were used to this PIV system. An Nd:YVO\(_4\) laser (50 mJ) was applied for the light source of the flow visualization. The pictures of the flow fields were taken by a CCD camera (SONY Shape Vision 1300DE) with the resolution of 1360×1024 pixels.

The closed-circuit wind tunnel is utilized for flow measurement of MAV, which has a squared cross section of 400×400 mm, length of 400 mm. Oil mists were used for the tracer of PIV measurement. The diameters of the particles are from 1 \(\mu\)m to 3 \(\mu\)m. The density of the oil-mist in the closed-circuit was controlled by the fog generator of DANTEC SAFEX F2010. The density of the mist was kept almost constant to retain the quality of the pictures.

The frequency of the flapping airfoil was about 5 Hz, which was same order of the sampling frequency of the PIV system. To study the flow field of the flapping airfoil, it is required to visualize the flow field of the various airfoil positions. A phase-averaging method was carried out to capture the time-series data of the
vorticity fields. A reference marker is attached on the gear box of the flapping mechanism as described below, and the trigger signal was obtained from the optical tachometer. The camera and laser was synchronized by this trigger signal. The PIV data were averaged at the same phase-angle of the trigger signal. The number of phase-averaging was 50 at each phase angles.

2.2. Flapping Airfoil and its Mechanism

To study the insects’ flight, a flapping machine was developed. In this study, a horsefly (*Epistrophe balteata*) was chosen for a model of flapping airfoil. The horsefly has a pair of wings, its flapping-motion is simple, which is useful for the basic study of the insects’ flight. Moreover, horseflies inhabit broadly all over Japan. Horsefly is therefore suitable for capturing and breeding in the laboratory.

The length and weight of horsefly’s body is about 10 mm and 25 mg, respectively. The flapping frequencies of horsefly are from 200 Hz to 250 Hz. The size of the real insects is too small and flapping frequency is too fast for the conventional PIV system. In order to quantitative measurements, 10 times expanding model of the real insects was designed. In the similarity law of flapping motion, flapping frequency corresponds to 1/100 times frequency. The frequency is about 2-2.5 Hz of the expanding model.

![Figure 1. Gear and link mechanism of flapping machine](image1)

Figure 1 shows the gear box and link mechanism of the flapping machine. The specification of the machine is shown in Table 1. The origin of the flapping angle is set to horizontal plane. A shape of the wings of horsefly was traced by microscope, and 10 times expanding model was reproduced. Figure 2 shows schematics of flapping machine.

An airfoil of insects has “Wing Veins”. The veins play an important role in strength structures, but also aerodynamic equipments. However, in this study, the vein is not considered. Although horsefly has a pair of wings, the present flapping-machine has only one moving airfoil with limitation of the gear box design.

Figure 3 shows time-series pictures of feathering motion of the developed flapping machine, which was obtained by high-speed camera (PHOTRON FASTCAM-512PCI). The airfoil was turned by 2.5 degrees in each angle of flapping motion. The airfoil was inclined to 100 degrees against the horizontal axis at bottom dead center (BDC). This angle is necessary to reduce the negative lift during the upstroke motion.

<table>
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<tr>
<th>Table 1. Specification of flapping machine</th>
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<tr>
<td>Wingspan</td>
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<td>Gross Weight</td>
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<td>Flapping Frequency</td>
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<td>Flapping Angle</td>
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<td>Rotating Angle</td>
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![Figure 2. Schematics of flapping machine](image2)

The spanwise length of the flapping airfoil is 100 mm. The chord length is increasing along the spanwise length from gear box side to spanwise length of 65 mm, and it is decreasing along the spanwise length from this point to the tip. The PIV measurements were carried out at the maximum chord-length. The mean flow velocity is set to 0.2 m/s which correspond to 1/10 speed of horsefly’s flight. The Reynolds number (4.5 \( \times \) 10^2) based on the chord length and the uniform velocity same as the real insect. Since the torque of driving motor is not enough at low revolution, the flapping frequency was set to 5 Hz. The reduced frequency was 2.2, which was beyond that of horsefly (0.5-5). PIV images were obtained at phase angle of 30 degrees each.

![Figure 3. Time-series pictures of feathering motion](image3)
2.3. Numerical Methods

Since aerodynamic forces of the flapping airfoil is extremely small. As a result, it is difficult to remove the vibration and resulting forces. To estimate the aerodynamic forces of the flapping airfoil, numerical simulation was carried out by using discrete vortex method (VFS VOs-2D; College Master Hands).

Since the vortex method is mesh free algorithm, moving boundaries such as the flapping airfoil is easy to handle. Vorticity elements are automatically introduced in the flow field to solve the continuity equation on the surface of the bodies (Kamemoto, K (1995)). Therefore, flow separations can be solved by this type of vortex methods.

3. Results and Discussions

Since the angle of attack is change during the flapping motion, lift and drag forces are instantaneous change. The coordinate system is fixed at horizontal and vertical axis. The lift and drag of the flapping airfoil should be estimated by the average value of one cycle of the flapping. Figure 4 shows the lifting force of the flapping airfoil with and without twisted motion. The sinusoidal motion generates positive and negative lift in one cycle, the absolute values are almost same as the positive and negative. Therefore, total lift is almost zero in one cycle.

The maximum lift feathering motion is smaller than that of the sinusoidal, however, the total lift of the feathering motion becomes larger than that of the flapping airfoil without the twisted motion. The lift coefficient had negative value at the middle of upstroke in the sinusoidal motion, however, it was improved by the feathering motion. At middle of the down stroke, lifting force of feathering motion is smaller than that of sinusoidal motion. This result shows that the present twisted motion is not optimized for the flapping airfoil. However, it is confirmed that lifting force can be increased by the feathering motion.

4. Conclusion

The flapping machine imitating insect's motion was developed, and flow fields around the flapping airfoils were measured and simulated by using the PIV measurement and vortex method. The leading-edge vortex plays an important role in generating the lifting force. The wake-capture is also important to reduce the negative lift during the upstroke motion. The combination of the flapping and twisted motion is key technology to develop the flapping MAV. However, link and gear mechanism has limitation of mechanical and weight problems. It seems that elastic wings are suitable to generate large lifting force with flapping motion.

5. Acknowledgement

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6. Reference


Figure 5. Contours of vorticity, velocity vectors and distribution of the vortex elements